USE OF GUIDED WAVES FOR DETECTION OF INTERIOR FLAWS IN LAYERED MATERIALS

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INTRODUCTION AND BACKGROUND

The increasing use of composite materials in structurally critical applications necessitates the use of accurate and fast nondestructive evaluation (NDE) techniques. Ultrasonic NDE of continuous fiber reinforced polymer matrix composite materials faces several challenges, including the inspection of highly attenuative thick composites. The ultimate goal of this research is to develop a NDE system that can quickly examine layered composite materials through their entire thickness, yet with greater sensitivity than existing methods.

The traditional method of ultrasonic NDE for composite materials is pulse-echo inspection. In this technique, longitudinal ultrasonic waves are fluid coupled to the composite at normal incidence to the surface (and thus, in most cases, normal to the laminae). Attenuation of the sound wave significantly reduces the depth to which a composite can be inspected. Attenuation in composites is primarily the result of three factors. First, the polymer matrix materials tend to be very attenuative. Second, sound waves propagating at normal incidence to the laminae encounter many acoustic interfaces. At each interface, part of the wave is reflected resulting in less acoustic energy being transmitted across the interface. Third, sound waves are scattered from the main beam by fibers and tows.[1] One obvious way to increase penetration depth is to reduce the frequency of the sound wave, however this also reduces the sensitivity.

Another method of ultrasonic NDE of composites involves plate, or Lamb, wave inspection. This method uses an angled incident beam to generate a plate-type mode in a plate or shell shaped composite structure. Usually, a receiving transducer is used to detect the signal. This method is well suited for detecting large or extended flaws or for determining bulk material properties; however the long wavelengths of the modes typically used limit their ability to precisely localize a flaw or to detect small flaws. [2-6]

PROPOSED TECHNIQUE

In the proposed technique, we attempt to exploit the waveguide properties of a composite laminate. A unidirectional fiber reinforced composite lamina consists of fibers or fiber tows (bundles) running parallel to one another in a single direction. A number of these laminae are stacked at various orientations, thus forming the composite. The speed of sound in a given direction in a lamina is dependent upon the orientation of the fibers relative to the direction of propagation of the sound wave. To obtain an order of magnitude approximation of the velocity in a given layer, a spring model of a composite was used to determine Young's Modulus, E, in the directions parallel and perpendicular to the fiber directions, and the density, ρ. The velocity in these two directions was determined (by $c \sim (E/\rho)^{1/2}$) to be approximately 2,000 m/s perpendicular to the fibers and 10,000 m/s parallel to the fibers.

Using these values, a section of composite material is considered which consists of three "layers". (Fig. 1) The central lamina is of thickness 2h and has sound speed corresponding to fibers running perpendicular to the direction of sound propagation. The bounding layers are considered to be semi-infinite with sound speed corresponding to fibers running parallel to the direction of sound propagation. The severe velocity mismatch in adjacent layers results in little interaction between layers. The wave equation is solved looking for homogenous solutions which satisfy continuity of displacement and continuity of traction as the boundary conditions.

Here, we suppose: $$\rho_1 = \rho_2 \; ; \qquad c_1/c_2 \equiv \epsilon \ll 1 \tag{1}$$

Solve: $$\nabla^2 u_{(1,2)} + k^2_{(1,2)}\, u_{(1,2)} = 0 \tag{2}$$

$$u_1(\pm h) = u_2(\pm h) \; ; \; c_1^2 \partial_y u_1(\pm h) = c_2^2 \partial_y u_2(\pm h) \tag{3}$$

Lowest Mode: $$u_1 \approx A \cos(\frac{\pi y}{2h})\, e^{ik_0 x} + \mathcal{O}(\epsilon^2) \tag{4}$$

$$u_2 \approx \frac{-\epsilon^2 A}{k_0 h}\, e^{-k_0(|y|-h)}\, e^{ik_0 x} + \mathcal{O}(\epsilon^4) \tag{5}$$

where $k_0 \approx k_1 \sqrt{k_1^2 h^2 - \pi^2/4}$.

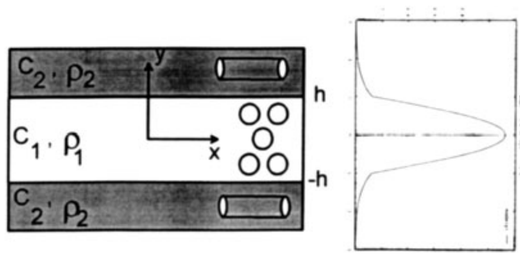

Fig. 1. A schematic of the three layered media used for calculating the containment of a mode to a single layer. The directions of the fibers are shown to indicate the relative speed of sound in the direction of propagation in each layer. Also shown is the amplitude of the lowest mode which propagates in the center layer.

The lowest symmetric mode is contained, for the most part, within the central lamina. (Fig. 1)

Here we attempt to excite a guided mode confined to a single layer as described above. Information from successive scans of adjacent layers are combined to comprise an evaluation of the entire composite.

POTENTIAL ADVANTAGES

There are several potential advantages to the proposed testing technique which justify further research into its practical application. Since the guided mode used for inspection will be contained almost entirely within the layer which is being inspected, any flaws detected must be present either in the layer or at the layer boundaries. In other words, the specific layer which contains the flaw is known.

In addition, the proposed method is insensitive to "flaw shielding". Traditional ultrasonic testing methods can have damage at a deep layer obscured by damage near the surface. This results from enough of the sound energy being reflected by the near surface flaw and attenuated in succeeding layers to prevent a significant return signal from the deeper flaw. Sound waves traveling within a layer, however, are not affected by such shielding.

Another advantage is that general part geometries can be inspected. A restriction that is common to traditional inspection with plate waves is that the inspected area must be plate or shell shaped. Since the proposed technique interrogates a single layer at a time, only the shape of the layer is important. Therefore, the overall part shape can be any geometry so long as it permits the layers which must be inspected to be continuous and roughly uniform. Additionally, the high frequency guided modes achieve greater sensitivity than do traditional methods. A primary obstacle to the use of high frequencies for composite inspection is the rapid attenuation of such frequencies when inspecting a composite at normal incidence with respect to the laminae. Since the proposed technique uses guided waves which propagate along a lamina rather than through several laminae, this source of attenuation is eliminated.

A final benefit would be the ability to inspect each layer a strip at a time, rather than point by point. Strips spaced at the desired sensitivity limit could be scanned, thus resulting in a scanning technique much faster than a B- or C-scan.

RESEARCH ISSUES

There exist several obstacles to overcome in the implementation of the proposed technique as a practical NDE method for composites. Determination of which modes will propagate contained within a single lamina is one. This problem may be exacerbated if a case by case analysis of the materials is necessary to determine the best guided mode in each. In addition, the modes themselves are dispersive, making data interpretation more difficult.

More significant, however, is the problem of exciting and detecting the modes within the desired lamina. The incident sound wave may have to propagate through a number of upper layers and then excite the desired mode in the lamina being inspected. Moreover, in exciting the desired mode in a specific lamina, it will be difficult not to excite the same mode in similarly oriented laminae. Once the mode has been excited, detection of energy scattered from or reflected by flaws is required. This energy must propagate out of the composite to a detector. The solution to these problems are partially linked to the identification of a suitable mode for inspection.

EXPERIMENTAL SETUP

A number of experiments were conducted to evaluate the potential merits of the proposed inspection method. Since the purpose of the experiments was a preliminary examination of the proposed technique, a simple model laminate was used and the method of introducing the guided wave to the desired lamina was simplified. There were three goals to these experiments. The first goal was to generate a plate type mode with the existing equipment. Second, to demonstrate the concept, the identified mode was used to inspect a model composite laminate. Two simulated flaws in the laminate were used, an interface type flaw and a flaw within the layer. The final goal was the experimental investigation of the containment of the wave to the desired lamina.

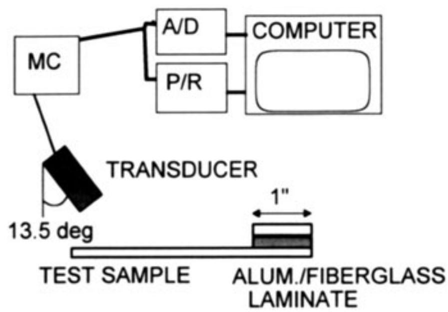

Fig. 2. A schematic of the ultrasonic testing equipment and experimental setup.

The experimental setup is shown in the schematic. (Fig. 2) A 486dx/33 Gateway computer operating a 100 MHz A/D board and a SR 9000 P/R (pulser/receiver) card was used in conjunction with a high precision motor control system (Matec, Marlboro, MA) to operate the transducer and position it in the immersion tank. The transducer used was a Harisonic 5 MHz immersion transducer with a 1/4 in. diameter element spherically focused at 1 in. The angle of the transducer with respect to the normal was set at approximately 13 degrees.

The model laminate was 2 layers of 0.04 in. thick (3.5 in. wide) aluminum sandwiching a fiberglass layer. (Fig. 2) The fiberglass layer consisted of 3 layers of plain weave glass (10 x 10 tows per in., 6 oz/yd^2), approximately 0.03 in. total thickness, in a polyester matrix. The length of the bottom aluminum plate was extended with respect to the rest of the laminate to permit easier generation of the guided mode. Simulated flaws were machined into the bottom layer.

EXPERIMENTAL RESULTS

In the first experiment, the goal was to determine if a 0.25 in. silicone filled hole could be detected in the bottom plate of the sample laminate using the guided mode. (Fig. 3A) The transducer was positioned over the bottom lamina at an angle of 13 degrees with respect to the normal, where the maximum signal response as a function of angle was detected. When the guided mode was generated away from the position of the hole, the top scan was observed. (Fig. 3B) The initial spike on the scan is the backscatter of the sound pulse from the top surface of the bottom plate. The noise surrounding the initial sharp spike is due to surface roughness of the sample. The next group of spikes is a reflection of the guided mode from the right edge of the plate (see Figs. 3A-C). Note that the pulse has dispersed considerably.

When the transducer was positioned such that the hole was between the sound source and the edge, the bottom scan was observed. (Fig. 3C) Note that the reflection of the guided mode from the edge of the hole is represented by a spike of greater amplitude and shorter return time than the signal from the right edge in Fig. 3B. The intermediate reflection also causes the amplitude of the return signal from the right edge of the plate to be reduced considerably.

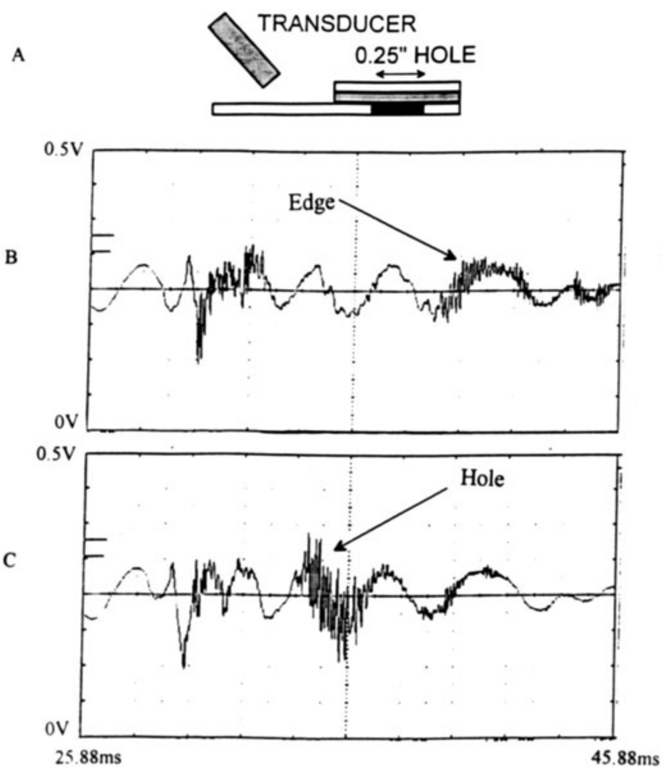

Fig. 3. (A) Schematic of layered test sample with a 0.25 in. diameter hole in bottom plate. (B) Return signal away from hole in bottom layer. (C) Return signal with transducer aligned with center of hole in bottom layer.

In the second experiment, a 0.5 in. diameter indentation was flat milled 0.01 in. into the bottom plate at the interface with the fiberglass. (Fig. 4A) The transducer was positioned as before. The top scan is observed when the guided wave is introduced such that it can propagate to the edge without encountering the simulated interface flaw. (Fig. 4B) In this experiment, the initial spike reflected from the test lamina is much cleaner than in the previous experiment due to the roughness of the sample surface being reduced by sanding with fine sand paper (400 grit/in^2). The larger amplitude of the reflected signal from the edge in Fig. 4B versus Fig. 3B is due to a smoother plate edge. It was observed that the finish of the plate edge and its orientation with respect to the incoming guided mode affected the amplitude of the returned signal; thus, efforts were made to keep the edge roughness and angle uniform.

In the bottom scan, the guided mode is introduced so that it encounters the simulated interface flaw before it reaches the edge of the plate. (Fig. 4C) As in the case of the through-thickness hole, the return time of the reflected signal is reduced, due to the closer proximity of the transducer to the flaw than to the edge of the plate. The amplitude of the reflected signal from the edge of the plate is again reduced due to the reflection from the simulated interface flaw.

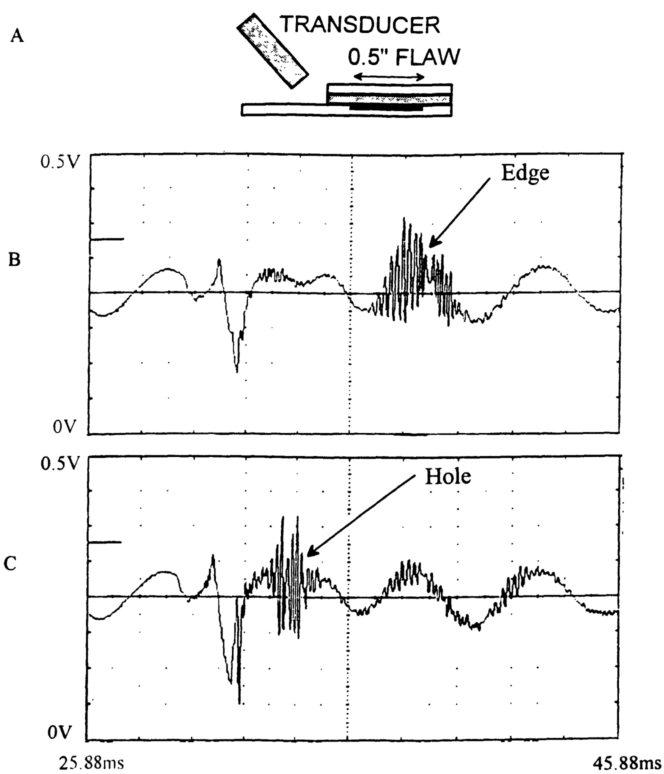

Fig. 4. (A) Schematic of layered test sample with a simulated 0.5 in. diameter 0.01 in. deep interface flaw in the bottom plate. (B) Return signal away from the simulated interface flaw. (C) Return signal from front edge of interface flaw.

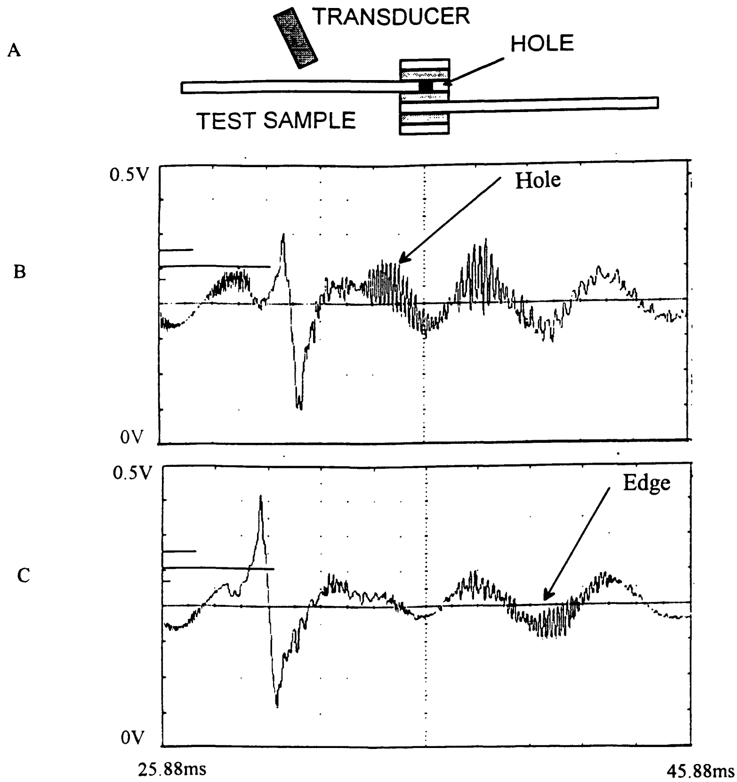

Fig. 5. (A) Schematic of test sample with seven layers, one of which contains a 0.25 in. diameter hole. (B) Reflection from layer with hole. (C) Reflection from layer without hole.

The final experiment was conducted to examine experimentally the degree to which the guided mode remains contained within the aluminum layer. A fiberglass/aluminum laminate was constructed as shown in the figure. (Fig. 5A) Note that the laminate section has increased from 3 to 7 layers but that the constituent materials and individual layer thicknesses remain the same. When the layer containing the silicone filled hole was examined with the hole positioned between the transducer and the edge of the plate, the hole was detected as before. (Fig. 5B)

When the sample is flipped 180 degrees and the layer without the hole is inspected, only the edge of the plate is detected. (Fig. 5C) This indicates that over the observed distances the guided mode being used does not spread to adjacent layers strongly enough to detect a significant flaw. This would mean that flaws detected with a guided wave on a specific layer are present only in that specific layer or at interfaces with neighboring layers. This will help to localize flaws.

CONCLUSIONS

A new technique has been proposed for higher frequency inspection of thick laminated composites. This method utilizes guided modes to detect flaws on a layer by layer basis. Preliminary experimental results were presented in this paper to demonstrate the feasibility of such a method.

The generation of a guided mode in the model laminate was achieved. The guided mode generated was used to detect large simulated through-thickness flaws. The modes were also capable of detecting simulated interface flaws. Finally, the guided mode used was, for the most part, contained within a single layer over short regions.

The future work on this project can be broken down into three areas. First, an analytical model (dispersion analysis) will be developed to predict the propagation of the guided modes in the lamina and for comparison to the experimental results. This will eliminate the trial and error approach to identifying suitable guided modes for inspection. The resulting dispersion analysis will be able to predict the effect of frequency and incident angle on the modal excitation. Second, more realistic laminates will be used. The lamina will be anisotropic, the dimensions of the lamina will more closely approximate realistic composites, and practical methods of exciting and detecting the guided modes will be investigated. Finally, the sensitivity limits of the proposed technique will be investigated.

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